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NEXT GENERATION LIGHT SOURCE R&D AND DESIGN STUDIES AT LBNL *

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Abstract

LBNL is developing design concepts for a multi-beamline soft x-ray FEL array powered by a superconducting linear accelerator, operating with a high bunch repetition rate of approximately one MHz [1–3]. The CW superconducting linear accelerator is supplied by an injector based on a high-brightness, high-repetition-rate photocathode electron gun. Electron bunches are distributed from the linac to the array of independently configurable FEL beamlines with nominal bunch rates up to 100 kHz in each FEL, and with even pulse spacing. Individual FELs may be configured for different modes of operation, and each may produce high peak and average brightness x-rays with a flexible pulse format, and with pulse durations ranging from sub-femtoseconds to hundreds of femtoseconds. In this paper we describe conceptual design studies and optimizations. We describe recent developments in the design and performance parameters, and progress in R&D activities.

NEXT GENERATION LIGHT SOURCE

The Next Generation Light Source (NGLS) is a scientifically transformative new facility in the early stages of planning. As currently envisioned, it will include an initial array of 3 independently configurable X-ray free-electron lasers (XFELs), upgradeable to 10 XFELs, powered by a superconducting linear accelerator and capable of delivering ultrafast (sub-femtosecond to hundreds of femtosecond), high brightness (up to 10^{12} photons/pulse), high-resolution pulses of soft X-rays (≤ 6 keV, with reduced flux at higher energies) at high repetition rates (up to 1 MHz) because of its superconducting accelerator design (Figures 1 and 2). These features define the experimental potential of this planned facility and distinguish it from existing synchrotron light sources, and other XFELs in operation or under construction which have a repetition rate that is 1–4 orders of magnitude lower (Figure 2). The high pulse repetition rate with uniform pulse spacing is a singular feature of the NGLS, which will enable time resolved experiments and allow the acquisition of billions of X-ray “snap shots” within experimentally practical time frames (hours, not days).

The NGLS will also allow a greater average coherent photon flux than is currently available at existing X-ray laser sources. Uniform spacing of the X-ray pulses will further allow for shot-by-shot sample replacement and data collection. Hence, the NGLS will have useful and distinct features.

MACHINE OVERVIEW

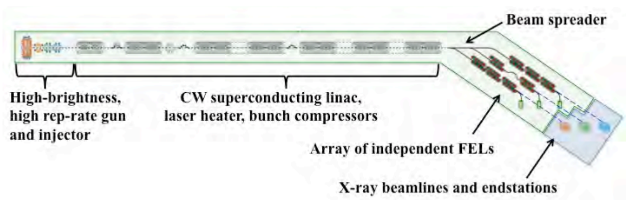

Figure 1: Schematic layout of the NGLS.

Figure 1 shows the main machine components. This layout has been developed utilizing a number of tools, including parametric studies using analytical models, and beam dynamics studies using tracking codes. Our development of modeling capabilities is described in [4,5].

Bunches with the required high brightness will be generated at the desired high repetition rate by a state-of-the-art VHF electron photo-gun, and will undergo emittance compensation and compression by ballistic and velocity bunching through the injector. Further compression will occur through magnetic chicanes in the linac before acceleration to the final beam energy.

The machine is designed for maximum bunch charge of 300 pC and nominal 1 MHz repetition rate (i.e an average current of 300 μA), and with upgrade paths consistent with a range of lower bunch charge at increased rate while maintaining average current <1 mA. We note that the gun and linac can accommodate a wide variety of bunch time structures, and our conceptual design allows flexibility to increase versatility in performance.

The nominal electron beam energy of 2.4 GeV has been chosen so as to be able to produce tunable FELs with up to 1.2 keV (1 nm) photons in the fundamental, while using available undulator technology (periods of about 19 mm, and minimum K-values of 1.6). Maintaining a small accelerator footprint and reducing cost are also considered. Development of undulator technology, in particular superconducting devices, would greatly benefit such a facility in both performance and cost; LBNL has an active R&D program in developing this technology [6].

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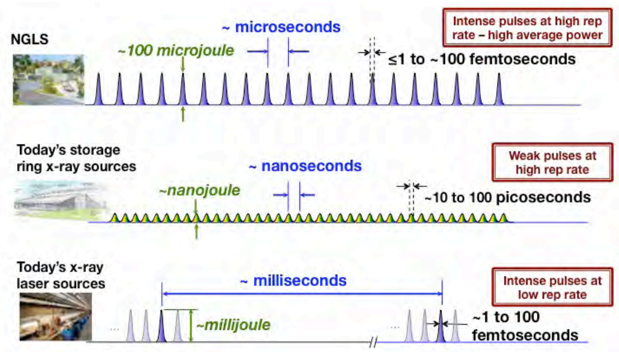

Figure 2: Comparison of pulse characteristics at existing and planned light sources.

Figure 3 shows the major components of the machine, together with beam parameters at select points.

Injector

The photoinjector is designed to operate at 1 MHz repetition rate and deliver the nominal 300 pC bunch charge, although up to 1 nC pulse charge may be possible, and higher repetition rate but at correspondingly lower charge. The electron beam is produced at a high quantum efficiency (QE) photocathode installed at the end of a re-entrant nosecone mounted in a 187 MHz cavity operating in CW mode [7]. A drive laser using commercially available technology illuminates the photocathode, and a "bucking" solenoid integrated into the nosecone of the gun controls the magnetic field at the cathode surface. Along the beam transport line and following the gun are a solenoid, followed by a buncher cavity, and then by a second solenoid. These elements initiate emittance compensation while simultaneously performing "ballistic" bunch compression. After the second solenoid is an accelerating cryomodule, labeled L0 in Fig. 3, and containing seven 1.3 GHz CW TESLA-like superconducting 9-cell cavities, with independent control of accelerating field phase and amplitude at each cavity. This cryomodule, identical to the main linac cryomodules, accelerates the beam from 750 keV at the gun exit and performs velocity bunching by de-phasing the RF with respect to the maximum acceleration phase in the initial cavities. The energy at the exit of the injector is about 90 MeV. The low-energy beam at the exit of the gun places special demands on the injector configuration, and beam dynamics studies showing required performance are presented in [8].

The APEX experiment at LBNL is under way to demonstrate the required injector performance [9–12]. We have procured cesium telluride (Cs_2Te) photocathodes as used at other facilities, and in addition we collaborate with BNL and Stony Brook University, in development of high-QE positive-electron-affinity semiconductor photocathodes such as di-potassium cesium antimonide (K_2CsSb) [13–15]. Both cathodes offer initial QEs significantly higher than 5% with photoemission in the UV for Cs_2Te and in the visible for the K_2CsSb. The 1052 nm ytterbium-fiber photocathode laser for APEX, developed in collaboration with UC Berkeley and LLNL,

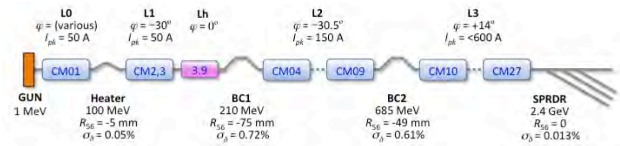

Figure 3: Schematic view of the major accelerator components. Beam phase, current, energy, energy spread, and dispersion in chicanes are shown.

delivers 0.7 W in the IR at 1 MHz repetition rate, with crystal-based harmonic generation to 526 nm (~240 mW) and 263 nm (~85 mW) for the two types of cathodes. The laser pulse is stretched to provide the required long pulses (~50 ps) for the low-gradient gun [11].

Linac

Choices for beam energy and pulse repetition rates necessitate the adoption of SCRF technology for the linac. Designed to accept electron bunches at about 90 MeV energy from the injector, the linac provides acceleration up to ~2.4 GeV, and bunch compression, before directing the beam to the spreader for distribution into the separate FEL undulator lines. The proposed layout, based on the preliminary choice of 1.3 GHz TESLA-like superconducting cavity technology, consists of seven main sections. The first section, the laser heater, interfaces the linac with the injector, and is intended for control of the beam's uncorrelated energy spread and for stabilization of the beam dynamics. The beam is then accelerated in Linac 1 (with ~100 MeV energy gain), conditioned by passage through a 3.9 GHz third-harmonic RF structure, compressed through a single-chicane bunch compressor at about 210 MeV energy, and then further accelerated to ~685 MeV in Linac 2. A second bunch compressor allows for further manipulations of the longitudinal phase space, and the final energy of 2.4 GeV is achieved in Linac 3, the last linac section. Given the 30-50 A range for the peak current out of the injector, a 10-17 compression factor is required in the linac. Beam dynamics studies are described in [16]; an alternate approach is explored in [17].

Following the linac is a beam spreader, designed to deliver individual bunches to the array of FELs. Use of an electromagnetic septum downstream of a weakly-deflecting pulsed kicker (0.6 mrad, at 100 kHz rate) allows the kicker tolerances to be significantly relaxed [18,19]. The final transport line in the spreader is configured from DC components, and can accommodate the full rate from the linac.

A CW linac operating at high bunch rate offers opportunities for feedback control to achieve excellent stability in beam position, timing, energy, and bunch length, as well as some challenges in diagnostics designs. R&D at LBNL in these areas is described in [20,21].

The lattice design includes beam collimators placed at various locations in correspondence to the local maxima of the dispersion function [22].

FELs

The NGLS design incorporates multiple FEL beamlines, with an initial array of 3 independently configurable X-ray XFELs, upgradeable to 10, each of which will deliver X-ray beams with distinctive photon attributes. The primary spectral range will extend from 280 eV to 1.2 keV at the fundamental of the undulator emission, and up to approximately 6 keV at much reduced intensity by the generation of harmonics. FEL seeding is planned, to impart temporal coherence approaching fundamental transform limits, to produce pulses with duration as short as ~250 attoseconds, with the possibility of some control over chirp or longitudinal pulse-shape, and with synchronization of the laser-seeded X-ray pulses to end-station lasers with femtosecond precision. One of the FELs will be capable of producing "two-color" X-ray pulses, while the other FELs will provide better energy resolution with longer pulses and high temporal coherence achieved through self-seeding. The furthest downstream FEL will be capable of operating at the full repetition rate of the linac, by transporting electron beam through DC components, thereby providing very high average power X-ray beams, with up to ~100 W coherent power.

The high repetition rate offers unique capabilities, with more energy per unit bandwidth, more average power, and shorter pulses, with controlled trade-off between time and energy resolution, as compared to other XFELs.

The success of hard X-ray self-seeding at the LCLS [23] has shown the feasibility of this conceptually simple approach, and two of the NGLS FELs are currently envisioned as self-seeded. An R&D project has begun to demonstrate soft X-ray self-seeding at the LCLS, in collaboration with SLAC. The self- seeded beamlines will in principle be capable of operating at the full machine repetition rate, although the initial beam spreader will accommodate this bunch rate only in the furthest downstream FEL. The first two FELs, fed by pulsed kickers in the spreader, will operate at an initial rate of up to 100 kHz.

FEL designs using undulators of two different periods are being developed to maximize tuning range; the shorter period device is used for higher energy photon production in which case the longer period device K-value is smaller than desired. The high repetition rate naturally leads to consideration of novel approaches for future implementation of oscillator FELs, as discussed in [24].

Operation with high average current leads to beam-induced heating of the vacuum chamber through the resistive wall impedance; studies suggest that this will be limited to an acceptable few W/m [25].

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